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Review

Aquaculture of paddlefish in the United States

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Abstract − Paddlefish are endemic to most rivers and tributaries of the Mississippi basin and are found in 22 states of the United States. In 1989, US Fish and Wildlife Service (USFWS) listed paddlefish as a category 2 species because data were lacking on its population status. In 1992, USFWS added paddlefish to the list of Appendix II of the Convention on International trade in Endangered Species of Wild Fauna and Flora (CITES) primarily due to concerns about illegal poaching in the international caviar trade. Therefore, paddlefish aquaculture will provide alternative fish sources for the marketplace in the era of strict federal and state regulations on wild populations. Aquaculture of paddlefish is in a research and developmental phase. Most broodstock are obtained from wild sources, though some mature fish have been developed in captivity. Artificial propagation techniques are resulting in > 80 % egg fertility. Larval paddlefish are initially raised in organically fertilized, zooplankton-rich (i.e. *Daphnia* sp.) ponds, and then trained on extruded trout/salmon diets until the juvenile fish are > 30 cm in total length. Tank culture is also an alternative for raising juvenile fish. Juvenile paddlefish, a filter feeder that requires zooplankton as its primary food, are being grown in reservoirs and in polyculture with channel catfish (*Ictalurus punctatus*) in Kentucky, Indiana, Missouri and Alabama. Production yields are 200–400 $kg \cdot ha^{-1}$ in polyculture and in reservoirs ranching resulted in 55–175 $kg \cdot ha^{-1}$. Reservoir ranching is ideal for caviar production; whereas, paddlefish (1.5 to 4.0 kg) cultured with catfish is for meat production. A system to produce all-female progeny through artificial propagation with sex-inverted, gynogenetic broodstock and attempting to develop optimal cryopreservation techniques for the milt of these unique broodstock is currently being tested. Value-added products such as hot and cold smoked paddlefish are the major effort being developed for the marketplace. Consumer acceptability of value-added products from paddlefish has been better than channel catfish. © 2001 Ifremer/CNRS/INRA/Cemagref/Éditions scientifiques et médicales Elsevier SAS

artificial propagation / fry culture / production systems / milt cryopreservation / value-added products / paddlefish / *Polyodon spathula*

Résumé – Aquaculture du poisson spatule (*Polyodon spathula*) aux États-Unis. Le poisson spatule est endémique dans la plupart des rivières et cours d'eau du bassin du Mississipi, et on le trouve dans 22 états des États-Unis. En 1989, Le Service américain « Poissons et Vie sauvage » (*US Fish and Wildlife Service*) classait le poisson spatule en catégorie 2, par manque de données sur le statut de cette population. En 1992, ce même service ajoutait le poisson spatule à la liste de l'Annexe II de la Convention sur le commerce international des espèces en danger de la faune et flore sauvages (CITES), ceci dû principalement au commerce illégal du caviar. Par conséquent, l'élevage du poisson spatule fournira une ressource alternative pour le marché, à l'ère des réglementations strictes fédérales sur les populations sauvages. L'aquaculture du poisson spatule est en phase de recherche et développement. La plupart des stocks de reproducteurs sont d'origine sauvage, bien que quelques poissons adultes aient été produits en captivité. Les techniques de propagation artificielle résultent à 80 % de la fécondation des œufs. Les larves de poissons spatules sont élevées dans un premier temps dans des bassins fertilisés organiquement et riches en zooplancton (ex. *Daphnia* sp.), puis nourris à base d'aliments extrudés, aliments destinés aux truites et saumons jusqu'à ce que les jeunes atteignent une taille supérieure à 30 cm. L'élevage en bac est aussi une alternative pour les poissons juvéniles. Le jeune poisson spatule, en tant que filtreur, demande du zooplancton comme nourriture de base ; il est élevé en réservoirs et en polyculture avec le poisson-chat (*Ictalurus punctatus*) dans le Kentucky, l'Indiana, le Missouri et l'Alabama. Les rendements sont de 200–400 $kg \cdot ha^{-1}$ en polyculture, et de 55–175 $kg \cdot ha^{-1}$ en réservoirs. L'élevage extensif en réservoir est idéal pour la production de caviar, tandis que les poissons spatules (1,5 à 4,0 kg) élevés avec le poisson-chat sont produits pour leur chair. On test actuellement un système pour obtenir uniquement des femelles par propagation artificielle d'inversion de sexe de géniteurs et en développant des techniques de cryoconservation optimale pour la laitance. Des produits à valeur ajoutée tels que le poisson spatule fumé à froid ou à chaud sont les plus importants efforts développés pour le marché. Les réactions des consommateurs sont plus favorables aux produits à valeurs ajoutées provenant du poisson spatule que ceux des poissons-chats. © 2001 Ifremer/CNRS/INRA/Cemagref/Éditions scientifiques et médicales Elsevier SAS

élevage d'alevin / système de production / laitance / cryoconservation / poisson spatule / *Polyodon spathula*

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1. INTRODUCTION

The American paddlefish, *Polyodon spathula*, is one of two living species of paddlefishes in the family Polyodontidae, the other being the Chinese paddlefish, *Psephurus gladius* (Mims et al., 1993a; Bellis et al., 1997; Wei et al., 1997). The American paddlefish, spoonbill catfish and spoonfish are among several common names given to this unique prehistoric fish. Paddlefish is one of the largest (90 kg, 1.8-m long) freshwater fish in the United States and is found in 22 states that have large rivers and impoundments within the Mississippi River basin and adjacent Gulf coastal drainage (Graham, 1997). Paddlefish are closely related to sturgeons that are a group of fish having a mostly cartilaginous skeleton (Bellis et al., 1997). Unlike most fishes, a paddlefish is a filter feeder most of its life that is able to remove zooplankton from the water as their main food source.

Paddlefish, like sturgeon, are highly valued for its grayish-black roe that is processed into caviar and for their boneless, firm, white meat. However, most paddlefish products are obtained only from wild caught fish. Overexploitation and contamination by organochlorine pollutants such as polychlorinated biphenyl (PCB) and chlordane have required that many state agencies close down this valuable fishery (Gunderson and Pearson, 1992). Furthermore, because of concern about illegal poaching for the international caviar trade, paddlefish were added to the Appendix II list of the United Nation’s Conference of the Parties of the Convention on International Trade of Endangered Species of Wild Fauna and Flora (CITES) in 1992 (Graham, 1997; Raymakers, 1999). This CITES listing prevents the import or export of paddlefish and their products into or out of the United States, respectively, unless a CITES permit is obtained through the US Fish and Wildlife Service.

Aquaculture of paddlefish is becoming an alternative for marketing this species when faced with strict federal and state regulations, stock depletion and/or closure of the capture fisheries. Further, commercial farming of paddlefish is needed to meet the growing demand for caviar and other value-added products in existing markets as well as to insure high quality farm-raised products for developing new market outlets. Currently, aquaculture of paddlefish is in a research/developmental phase in the United States. However, ongoing research and demonstrations have shown potential at the commercial level. This review provides basic information that is currently available about propagation, production and marketing of paddlefish in the United States.

2. ADVANTAGES AND DISADVANTAGES FOR PADDLEFISH AND ITS CULTURE

Paddlefish have many outstanding characteristics as a food fish. Paddlefish filter feed primarily on zooplankton throughout most of their life and grow rapidly (up 4.5 kg·year^{-1} as adults) (Semmens and Shelton, 1986; Onders et al., 2001). They can be harvested easily with gill nets or by seining. Paddlefish can be propagated artificially and juveniles raised intensively up to 35 cm (total length) in ponds, then grown for meat and/or roe extensively in reservoirs or intensively in ponds with channel catfish, *Ictalurus punctatus* (Semmens and Shelton, 1986; Mims, 1991). Paddlefish meat is firm and completely boneless with a beef or pork-like texture and is similar to sturgeon in taste and texture (Wang et al., 1995). Mature female paddlefish can produce about 15 % of their body weight in grayish-black roe (1.5 to 4.5 kg·fish^{-1}) which can be processed into caviar and sold at wholesale prices of US$ 65–143 kg^{-1} and at retail prices over US$ 400 kg^{-1}.

Some liabilities as a food fish include poor tolerance to low oxygen (< 30 % of oxygen saturation at a given water temperature), handling stress when water temperatures are above 21 °C, complexity of artificial propagation and juvenile production, juveniles vulnerable to bird predation, waiting period of at least 7 years before females produce eggs, and sacrificing the fish for caviar production.

3. PROPAGATION

3.1. Collection and transport of broodstock

Broodstock are generally obtained from the wild population because of their long maturation period ranging from 7 to 9 years in the southern region and 10–14 years in the northern region of the United States. Broodstock are captured in 15 cm or larger bar-mesh gill nets that are set in rivers and lakes in the winter or early spring (< 16 °C). Typically, males are smaller in weight than females by about one-third to one-half, and have minute tubercles on their head and opercular flaps. In contrast, mature females have few, if any, tubercles and swollen abdomens; and, the gonopore areas may be distended and reddish in color during the pre-spawning period. Broodstock can be transported to the hatchery in conventional hauling tanks holding about 1 000 L water supplied with agitation and oxygen and mixed with 0.3 to 0.5 % sodium chloride. Approximately 0.3 kg broodstock·L^{-1} water is a safe quantity for transport. Broodstock can be held in ponds until water temperatures are suitable for propagation.

3.2. Hormone induction of broodstock

Paddlefish can be propagated when the water temperatures are between 13 to 18 °C. Broodstock must be held in circular tanks (diameter ≥ 2.4 m) in the hatchery, in order for the fish to swim continuously and aerate their gills (known as ram ventilation). Water temperatures of 16 to 18 °C, flow rate exchange of 25 % of the total tank volume·h^{-1} and water saturated with oxygen (100 %; about 10 mg·L^{-1} at 16 °C) are optimal conditions for broodstock in hatchery tanks.

Broodstock should be injected intraperitoneally with LHRH analogue of des-Gly 10 (D-Ala6) LHRH ethylamide (Graham et al., 1986). Females should receive a total dosage of 100 μg·kg^{-1} body weight (BW) administered in a priming injection (10 μg·kg^{-1} BW) and a resolving injection (90 μg·kg^{-1} BW) 12 h apart. Females can be expected to ovulate in 12 to 24 h at 16 °C after the resolving dose. Males should receive a single dose of 50 μg·kg^{-1} BW when the females are given the priming injection; they will spermiate within 24 h and continue for 3 to 4 d (Linhart et al., 2000).

3.3. Milt and egg collection

For milt (sperm) collection, the fish is blotted dry around the gonopore area. Tygon tubing (diameter, 0.5 cm; length, 5 cm) attached to a 10-mL plastic syringe is inserted into the urogenital pore. With gentle suction, milt is collected from the fish. A large volume (50–100 mL) of milt can be obtained each time from one male for 3–4 d (Linhart et al., 2000). However, milt from three or more different males should be used to fertilize the eggs from each female in order to increase genetic diversity. Milt is checked microscopically by mixing one volume of milt with 100 volumes of hatchery water and 75–100 % of the sperm should be motile for 30 to 90 s (Cosson et al., 2000). If sperm motility is less than 75 %, the milt should be discarded. Milt can be collected several hours before use and stored without aeration in sealed containers placed in a refrigerator (4 °C) or on wet ice (ice sprinkled with water).

For collection of eggs, hand-stripping was the traditional method when culturists believed that the paddlefish could not ovulate all their eggs at one time. The method was labor intensive and often required three or more individuals to collect and fertilize a small portion of the eggs (120–150 mL) every 30 to 60 min over a 12-h period before the majority of eggs were removed.

Further investigations have indicated that all eggs did ovulate within 1 h; however, due to a unique oviductal system, all the eggs could not freely flow out of the fish. Therefore, two other methods have been adapted from the sturgeon industry to expedite egg collection: caesarean section (Conte et al., 1988) and the minimally invasive surgical technique, MIST (Stech et al., 1999). Caesarean section is a relatively quick, surgical method (30 min) to remove eggs through a 10-cm external abdominal incision; however, suturing is time consuming and muscular stress on the incision usually results in poor suture retention and low survival of broodstock. The MIST permits even quicker removal of ovulated eggs, about 10 min, and requires less handling than the other methods and no suturing. This method of egg removal involves a small internal incision (1–3 cm) in the posterior dorsal area of the oviduct (*figure 1*). This permits direct stripping of eggs from the body cavity through the gonopore, but bypasses the oviductal funnels (ostia). Regardless of the method used, eggs must be collected free of water. Female paddlefish between 9 to 36 kg can release between 70 000 to 300 000 eggs·fish^{-1}, respectively.

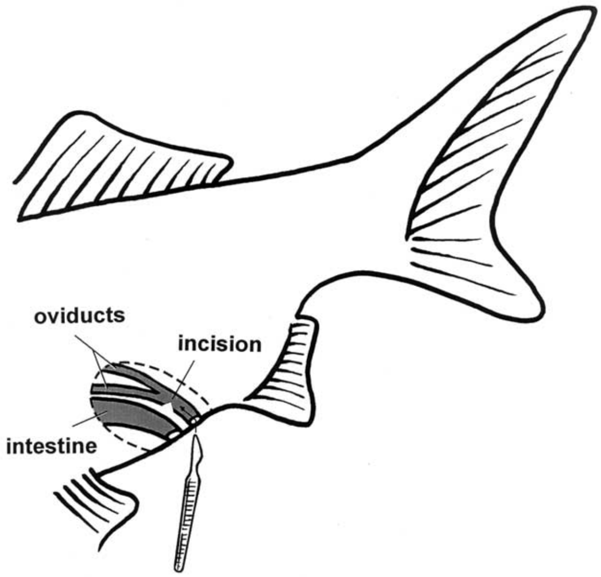

Figure 1. Schematic illustration of the minimally invasive surgical technique (MIST) for removal of ovulated eggs from paddlefish.

3.4. Fertilization and hatching

The eggs should be fertilized using the ‘wet method’. Milt is added to water at a 1:200 ratio (milt to water) and then immediately poured onto the eggs (10–15 mL milt·L^{-1} eggs; approximately 50 000 eggs·L^{-1}) (Graham et al., 1986). The fertilized eggs are stirred for 1 min then coated with Fuller’s earth (Sigma Co., St Louis, MO, USA) suspension (40 mL Fuller’s earth·L^{-1} water) for 20 min. The eggs are then rinsed, freed of Fuller’s earth, volumetrically measured and loaded into McDonald incubation jars (8 L) at about 75 000 eggs·jar^{-1}. Fungus can be controlled by frequent siphoning of dead eggs that float on the top layer and by maintaining water temperature near 18 °C. Larvae will hatch in approximately 6 d when eggs are incubated at 17 °C. Larvae require another 5 to 6 d before they will consume exogenous food. During this interim the mouth and foregut develop, and the residual yolk is absorbed. Dark pigmented material that can be seen in the spiral valve of the hindgut will be excreted at about the time exogenous feeding is initiated. Cannibalism is not uncommon during this period, especially if size variation occurs in the group.

4. NURSERY PHASE

4.1. Pond culture

Pond preparation should begin about 2 weeks before propagation. Ponds should be drained completely, and if possible dried. After fish have been propagated, the pond should be flooded with well water or with water from a reservoir that is filtered through a saran sock. Rice bran (11.4 % crude protein) has been recommended as the best organic fertilizer for paddlefish nursery ponds in Kentucky (Mims et al., 1991, 1993b). The quantities and application schedules of rice bran and liquid inorganic fertilizer (10-34-0) are indicated in *table I*. Other organic fertilizers such as cottonseed, soybean and alfalfa meals can be used, but quantities should be adjusted based on total nitrogen amount of 45 $kg \cdot ha^{-1}$. During the initial fertilization period (week 0), large zooplankton such as *Daphnia* sp. should be inoculated into the pond at 2 *Daphnia*$\cdot L^{-1}$ (Mims et al., 1991, 1993b, 1995a, 1995b). Other zooplankton such as copepods, rotifers, ostracods will not substitute for *Daphnia* sp. because other zooplankton are fast swimming and/or too small for larvae to capture. Larvae can be stocked at a rate of 60 000 $fish \cdot ha^{-1}$ in fertilized earthen ponds when water temperature exceeds 18 °C. Fish can grow up to 150 g and 35 cm in total length in about 6 months. During this time, survival rate can range from 30 to 80 %. Covering ponds with netting can control predation of paddlefish by aquatic birds such as cormorant and herons.

4.2. Tank culture

A flow-through tank system has been successful for the production of juveniles < 25 cm in total length. Source of the water can be ground water or surface water. Ground water should be aerated and heated to 22 °C. Surface water should be filtered and, if possibly, aerated and heated. Regardless of the source, incoming water should be tested for contaminants and other poor water quality parameters. However, with proper flow-through of about 25–50 % of the tank $volume \cdot h^{-1}$ water quality does not need to be monitored regularly, except for temperature and oxygen (see water quality section). Outdoor tanks should be covered with 95 % shade cloth to minimize sunlight and may provide some protection against predation by birds. Larvae are initially stocked at 2 $fish \cdot L^{-1}$. After 14 d, larvae should reach about 5 cm in length. To avoid crowding, fish should be reduced to 0.7 $fish \cdot L^{-1}$. After another 14 d, the fish should reach about 10 cm and the density should be further reduced to 0.2 $fish \cdot L^{-1}$. Feed should be delivered continuously on a belt feeder. Culturists should watch for fish swimming at the surface with their paddles above the water; a behavior known as 'billing'. Billing is a stress indicator of high density and reduction in fish density will usually stop this behavior. However, because of density reduction and large space requirements, fish are usually harvested at < 25 cm smaller than in pond culture (> 30 cm). In raceways, survival rates can range from about 50 to 80 %.

Table I. Quantities and application schedules of rice bran and inorganic fertilizer in paddlefish nursery ponds.

Week	Rice bran[1] ($kg \cdot ha^{-1}$)	Inorganic fertilizer[2] ($L \cdot ha^{-1}$)
0[3]	1 410	37
1	310	4.6
2	160	9.3
3	160	9.3
4[4]	160	9.3

[1] Other organic fertilizers can be used based on a total application of 45 $kg \cdot ha^{-1}$ nitrogen. [2] Inorganic fertilizer 10-34-0. [3] Fertilizers were applied to filled ponds three time per week during a 2-week period before stocking. [4] Fish should be offered 1.5 mm extruded diet during week 4.

5. FEEDING

In pond culture, larvae initially feed on relatively large, slow-swimming zooplankton such as *Daphnia* sp. These food items are preferred during the first 3 to 4 weeks (Mims et al., 1995b). Larvae cannot effectively filter-feed until their gill rakers are developed when the fish are about 12 cm in total length. During this initial feeding period, some culturists supplement the diet of the fish with trout/salmon crumbles (#00-02, 50 % protein) at a rate of 17 $kg \cdot ha^{-1}$. Once the fish are about 7.5 cm in length, they can be trained to accept extruded pellets (1.5 mm; 45 % protein). If fish are trained on a prepared diet, larger fish will accept larger-size extruded pellets. Feed conversion ranges from 1.5 to 2 kg $feed \cdot kg^{-1}$ fish.

In raceway culture, larvae can be trained on a sinking diet of trout/salmon (#00-02 crumbles; > 50 % of protein). Some culturists use a 1.5-mm extruded pellet once the fish reach about 7.5 cm in 3 to 4 weeks. Larvae are fed continuously by automatic belt feeders at 10 to 20 % of body weight (BW) for the first 7 to 10 d. Thereafter, a combination of automatic feeders and hand feeding is used to feed the fish at 5 to 10 % of BW until the fish are stocked into ponds or reservoirs. At this time, feed conversion ranges from 2 to 4 kg $feed \cdot kg^{-1}$ fish.

6. WATER QUALITY

Dissolved oxygen is particularly important; a daily oxygen-monitoring program is necessary to achieve maximum yields in ponds. Because paddlefish have a rostrum, they are unable to obtain oxygen present in the surface film of water, as many fishes do when dissolved oxygen is low (< 2 $mg \cdot L^{-1}$). It is recommended that the dissolved oxygen should be main tained above 30 % of saturation at any given water temperature to prevent stress or loss of paddlefish. Paddlefish can survive a wide range of water temperatures from above 0 to about 35 °C. Water temperatures for acceptable fish growth range from 15 to 27 °C. However, paddlefish handle best at stocking and harvesting when water temperatures are < 21 °C. Other water quality parameters are similar to those required by channel catfish, *Ictalurus punctatus*, pH 6–9, unionized ammonia < 0.2 mg N·L^{-1} and nitrite depends on chloride level.

7. DISEASES

Diseases have not appeared to be a problem in production of paddlefish in ponds or reservoirs, probably due to low stocking densities. However, a few diseases have been reported and studied for intensively-cultured paddlefish in raceways (Fries and Villareal, pers. comm.). One disease known as rostrum degenerative disease causes deformity of the rostrum including a narrowing and/or downward curvature. Both *Aeromonas* and *Columnaris* bacteria have been isolated from the rostrum and are believed to cause this disease. Chloramine-T at a rate of 20 mg·L^{-1} for 1 h has experimentally stopped the progress of this disease in raceways. Paddlefish have also been known to be infected with 'Ich' (*Ichthyophthirius multifiliis*). Salt treatment at 3 g·L^{-1} or water temperature raised to 30 °C for several days have been successful in eliminating this parasite in raceways.

8. PRODUCTION STRATEGIES

Reservoir ranching and pond polyculture with channel catfish are two practical systems to raise paddlefish for caviar and/or meat in the United States (Semmens and Shelton, 1986; Mims and Shelton, 1999; Onders et al., 2001). Production of paddlefish in both systems relies on the fertility of the system and the filter-feeding ability of paddlefish to remove naturally produced zooplankton, and requires little cost and management. It should be noted that diet-trained paddlefish stocked into these systems (low stocking rates) will switch to filter feeding and will not compete with the other fish for prepared diets.

8.1. Reservoir ranching

Reservoir ranching is an extensive aquacultural production system where young fish (< 30 cm) are stocked into a reservoir, permitted to forage on the natural food supply, and are harvested after 2 or more years. This system is a very economical one for paddlefish caviar production. It uses existing reservoirs that were primarily developed for the storage of water, flood control and hydroelectric purposes. It has been demonstrated that paddlefish stocked at low densities (10 to 20 fish·ha^{-1}) can reach 4.5 kg in about 18 months (Alabama and Kentucky, USA) and can be sold for their meat or permitted to grow until mature, and then harvested for their roe. Fish are harvested with gill nets with nearly 90 % efficiency (Onders et al., 2001). It is estimated that 55 to 170 kg·ha^{-1} could be harvested yearly depending on the fertility, food supply and temperature of the water. Ongoing research is further evaluating reservoir ranching.

8.2. Polyculture with channel catfish

Polyculture of paddlefish with catfish is a more intensive system than reservoir ranching. Paddlefish, stocked at 75 fish·ha^{-1} with catfish at 12 500 ha^{-1} have been reported to reach up to 3.2 kg in about 12 months (Kentucky). Production yields can range from 200–400 kg·ha^{-1}. Production of paddlefish stocked with catfish is limited by the ability of the pond system to produce zooplankton and by water quality. If feeding rates to the catfish are increased, this could cause an increase in the zooplankton productivity; and, higher yields of paddlefish could be expected. However, higher feeding rates to catfish will cause greater oxygen demand and possibly result in water quality problems. Fish can be harvested by seining with nearly 100 % efficiency. They are easily sorted by hand from the catfish and can be held in holding nets (< 15 °C) until loaded for transport to processing plant. Because of the typical harvest cycle for catfish (every 6 to 12 months), this system is best for paddlefish meat production; even though, the fish can be returned to the pond for further growth to maturity. More information is needed on production of paddlefish and catfish stocked at commercial operations in different areas of the southern region of the United States.

9. DEVELOPING TECHNOLOGY FOR PADDLEFISH AQUACULTURE

9.1. Monosex production of all-female paddlefish

Culture of monosex populations in aquaculture has several applications, and the increased caviar yield potential is a major justification for paddlefish (Mims and Shelton, 1999). A system is being tested to produce all-female progeny through artificial propagation with unique broodstock. The system involves three levels: gynogenesis (Mims et al., 1997), steroid-induced sex reversal (Mims et al., 1995c), and the use of neomales to produce all-female progeny (Shelton, 1986a) and is in the final stages of development. Assumptions involve (1) the presumptive XX-female sex determination, and (2) the effectiveness of induction techniques for chromosome manipulation and sex reversal developed for other fishes when applied to the paddlefish (Shelton, 1986b). Gynogenesis has been achieved in paddlefish through the use of UV-treated heterologous sperm to activate ova, which were then diploidized by heat shock to retain the second polar body (Mims and Shelton, 1995; Mims et al., 1997;

Shelton et al., 1997). Shovelnose sturgeon, *Scaphirhynchus platorynchus*, spermatozoa has been used as the donor based on anticipated compatibility of gametes. About 15–20 % of heat-shocked paddlefish eggs hatched as diploid larvae from egg batches with about 75 % normal viability. Progeny were then implanted prior to gonadal differentiation at about 20 week of age with slow-release capsules containing methyltestosterone. All untreated paddlefish gynogenotes examined have been females. About 90 % of treated genetic females were sex reversed to males (Mims et al., 1995c). Some of these presumptive XX-male paddlefish are being grown to sexual maturity to test their fertility and the final outcome of the program. In the future, if all female paddlefish could be produced through a breeding program, then profits on reservoir ranching would increase.

9.2. Cryopreservation of paddlefish milt

Cryopreservation of milt from paddlefish has only recently been reported (Brown and Mims, 1999; Mims et al., 2000). In brief, paddlefish milt were mixed with a cryoprotectant medium containing 2.4 M DMSO (dimethyl sulfoxide) in a ratio 3:1 (milt:medium, final concentration of DMSO was 0.6 M). The milt and cryoprotectant mixture was stored in 5-mL straws, frozen on dry ice (15 min) and stored in liquid nitrogen. For thawing, straws were immersed in a water bath at 20 °C for 15 s. Thawed spermatozoa were observed to have motility of 25 to 50 %, compared to 100 % motility for fresh spermatozoa. Thawed samples of paddlefish milt were used for insemination of large quantities of eggs (3 500 per trial) with standard fertilization procedures (coating of adhesive eggs) and incubation techniques (McDonald jars). Hatching of paddlefish (16 ± 2 %) from eggs fertilized with thawed spermatozoa was significantly lower ($P < 0.01$) than the hatching (90 ± 3 %) with fresh sperm. The decrease in fertilization ability of thawed spermatozoa could have resulted from low motility and damage of the acrosome (Ciereszko et al., 2000). Further investigations are ongoing to improve the quality and quantity of thawed spermatozoa to increase the hatching percentage of paddlefish.

10. VALUE-ADDED PADDLEFISH PRODUCTS AND MARKETS

10.1. Caviar

Traditionally, caviar was defined as salted sturgeon roe from fish caught in the Caspian Sea. However, the grayish to blackish colored eggs, prized for caviar, can be obtained from two families: the sturgeons (Acipenseridae, 26 species) and the paddlefish (Polyodontidae, two species). In all cases, the fish must be sacrificed to obtain quality caviar at this time.

In recent years, there has been a major decline in sturgeon stock from the Caspian Sea that is causing an increase demand for alternative supplies of caviar (Raymakers, 1999). Paddlefish caviar has often been used as an alternative product in the marketplace. Its caviar is most often compared to sevruga (*Acipenser stellatus*) caviar, the most popular of the Caspian Sea caviars. Paddlefish and sevruga have similar egg size (known as small grains) and a grayish color with a mild, less salted taste.

A 20-kg female paddlefish that is sacrificed can yield about 2 to 3 kg roe. Current market price ranges from wholesale prices of US$ 65 to 143 kg^{-1} to retail prices of over US$ 400 kg^{-1}. The caviar is marketed through buyers that sell to exclusive restaurants, gourmet shops and mail-order retail outlets. By raising paddlefish in ponds and reservoirs, caviar can be produced and marketed which could alleviate pressure on wild stocks. Further, the caviar evaluated from the cultured paddlefish has been described as having a more buttery taste (more fat in egg) than caviar from wild paddlefish. Recently, a blind taste test was done to compare cultured paddlefish caviar with the top three Caspian Sea sturgeon caviar (beluga, *Huso huso*; osetra, *Acipenser gueldenstaedti*; and *A. stellatus* sevruga) and cultured paddlefish caviar was tied for second with osetra and was second only to beluga. Lastly, contaminants were not found in cultured paddlefish caviar as sometimes found in caviar of wild stocks.

10.2. Meat

Paddlefish meat is firm and boneless and is very similar to sturgeon meat in taste and texture (Wang et al., 1995). Through taste testing, paddlefish meat has been well accepted by consumers. Even those who do not eat fish regularly liked paddlefish meat products. Recently, several smoked paddlefish meat products have been developed. Some of these have been well received in exclusive restaurants, gourmet shops and other sophisticated markets. Smoked paddlefish wholesales for US$ 20–24 kg^{-1} and retails for over US$ 40 kg^{-1}. Paddlefish meat also has been tested for surimi (imitation crab meat) production with positive results. Further development of value-added products from paddlefish meat is in progress.

11. CONCLUSION

Paddlefish have had a variable history as a food fish. More recently, popularity has increased through value-added products and the demand for caviar has placed considerable stress on the natural populations. The development of culture techniques have included improved artificial propagation protocol, intensive nursery production, pond and tank culture options, and advances in monosex production. Culture in the US may develop by integration with the channel catfish industry, but reservoir ranching is more likely to be the system that develops. It is important that federal and state agencies and the aquaculture industry work together to develop farm-raised paddlefish in the United States in order to provide a reliable supply of caviar and meat for commerce.

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